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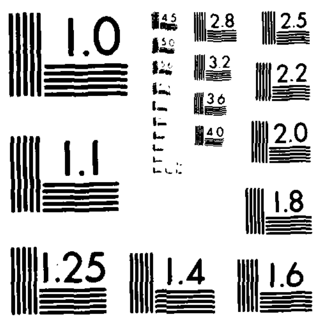

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FEASIBILITY OF BALLOON-BORNE OPTICAL MEASUREMENT OF C_n^2

C.A. Trowbridge and G. Davidson

PhotoMetrics, Inc.
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26 October 1981

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Investigation of an in situ method for determining altitude profiles of the optical index of refraction structure constant C_n^2 by balloon-borne direct optical measurement is described. Laser beam wander versus time may be determined with great precision utilizing a position sensing photodetector and C_n^2 derived from these measurements. The instrument con-

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20. Abstract (continued)

figuration, components, weight, power and telemetry requirements, and probable measurement sensitivity as a function of operational altitude range and duration of flight are considered.

FOREWORD

The program described here involved investigation of the feasibility of constructing a light weight balloon-borne instrument to determine the altitude dependence of C_n^2 by direct optical measurement of laser beam wander (spot dancing) induced by turbulence in the atmosphere. A method of obtaining the high measurement precision (on the order of $10^{-3}\mu m$) necessitated by the short optical path length, and preliminary instrument design are discussed.

The authors wish to express their thanks to Dr. A.F. Quesada, Program Manager, Dr. R.E. Good, and Mr. W.K. Vickery of AFGL for their continued encouragement and support, and to C.C. Rice who made important contributions to this report.

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SECTION I

INTRODUCTION

The purpose of the work presented here is to investigate the feasibility of constructing a balloon-borne laser-based instrument system for in situ direct optical measurement of the altitude dependence of the optical index of refraction structure constant C_n^2 (defined in Section II) in the turbulent atmosphere.

The reliability and performance of laser based communication systems and target designators is critically dependent on the optical propagation characteristics of the natural atmosphere. Turbulence induced variations in the local index of refraction along the laser beam's propagation path cause random perturbations in the phase of the transmitted wave which can result in distortion of the received beam image and scintillation of the received beam irradiance distribution. Furthermore, refractive index fluctuations can alter the angle of beam propagation, resulting in large and rapid spatial displacements (spot dancing) of the beam from its expected path through a nonturbulent uniform atmosphere.

Improvements in capability to predict statistically the path that a laser beam will follow through the turbulent atmosphere, that is, construction of accurate atmosphere propagation models, depends upon increased experimental knowledge of the variation of tropospheric and stratospheric turbulence as a function of altitude, latitude, time of day, and season. Section II presents a brief review of methods currently used to measure and characterize atmospheric turbulence. Design of the instrumentation and its operational parameters are discussed in Section III, and conclusions summarized in Section IV.

SECTION II

METHODS OF MEASURING C_n^2

This section presents a short critical review of experimental methods that have been used to characterize atmospheric turbulence relevant to laser propagation. Observable quantities related to local optical refractive index fluctuations include temperature measured by separated hot wire probes, laser beam propagation characteristics (lateral deflection, phase interference, and amplitude scintillation), phase or scintillation characteristics of single or double stars, and radar backscatter.

The optical index of refraction structure constant C_n^2 describes atmospheric turbulence in the context of optical beam transport applications. When the power spectrum of index of refraction fluctuations, $\phi_n(\vec{k})$, has a Kolmogorov inertial subrange, C_n^2 may be defined as

$$C_n^2 \vec{r}^{2/3} = < [n_1 - n_2]^2 >$$

where n_1 and n_2 are the optical index of refraction measured at two points separated by a distance $r = |\vec{r}|$. C_n^2 is also related to the power spectrum through

$$\phi_n(\vec{k}) = \frac{0.033\, C_n^2 \quad \exp(-k^2 \ell_o{}^2)}{[k^2 + L_o{}^{-2}]^{11/6}}$$

where k is wavenumber, and ℓ_o and L_o are the inner and outer scales of turbulence respectively.

Measurements of the spatial distribution of radar backscatter from atmospheric turbulence may in the future provide a least-expense method of monitoring index of refraction changes as a function of altitude (Ref 1). However, at present a reasonable doubt exists concerning the applicability of index of refraction at radio frequencies to propagation at optical frequencies, the basis for concern being the several orders of magnitude difference in wavelength. A further difficulty is the limited spatial resolution of radar backscatter probing; the scale sizes to which the method is sensitive are generally many times larger than those which will affect laser-light propagation.

Phase difference and scintillation of starlight propagating through the atmosphere and measured from ground-based observation sites provides another means for determining a C_n^2. By appropriately modeling the atmospheric structure, which requires assumptions of turbulent layers, and the layer thicknesses and altitudes, the vertical path integrated index of refraction has been determined using this method for as many as three atmospheric layers between 2 and 20 km altitude (Ref 2). Spatial filtering of scintillation frequencies and the use of path weighting functions can provide average values for up to 7 layers from 2.5 to 15 km (Ref 3). Path weighting functions however provide relatively poor altitude resolution, and furthermore long measurement integration times are required to produce precise data.

Under the assumption that optical refractive index fluctuations are due mainly to local temperature fluctuations, temperature probe measurements may be used to derive an optical C_n^2. The temperature structure function $D_T(\vec{r})$ is defined as the mean square of the temperature difference between two points separated by distance $\vec{r}$:

$$D_T(\vec{r}) = < [T_1 - T_2]^2 > .$$

When the turbulence is homogeneous and isotropic, D_T depends only on $\vec{r}$. Further, for the inertial subrange of turbulence in which $L_o >> r >> \ell_o$, where ℓ_o and L_o are again the turbulence inner and outer scales respectively, the temperature structure function depends on the 2/3 power of the distance between points at which temperature is measured:

$$D_T(\vec{r}) = C_T \; r^{2/3} ,$$

where C_T^2 is the temperature structure constant. Similarly the optical index of refraction structure function and structure constant may be defined as

$$D_n(\vec{r}) = C_n^2 \ r^{2/3} \ ,$$

and we may relate C_n and C_T to a close approximation by using the equation of the refractive index as a function of temperature T(K), pressure p(mb), and wavelength $\lambda(\mu m)$

$$C_n = \frac{77.6 \ p}{T^2} \quad (1 + \frac{0.00753}{\lambda^2}) \times 10^{-6} \ C_T \ .$$

The thermal method has been used near ground level and also on balloons. It assumes that the power spectrum of atmospheric turbulence has a Kolmogorov inertial subrange and that the conversion of C_T to C_n is valid only over the wavenumber extent of the inertial subrange. Further assumptions are made about the pressure and temperature charcateristics of the atmosphere. Although there is some question in the literature about the model on which the measurements are based (Ref 4), this technique has been the basis of all high resolution measurement of C_n as a function of altitude. Comparison of results from an optical method (intensity correlation of double star interference pattern) with the radiosonde thermal method shows up to an order of magnitude difference in C_n^2 (Ref 5).

The magnitude of laser beam scintillation over short atmospheric paths appears to be too small to allow measurement by currently available methods. Measurement of scintillation after propagation through laboratory generated, very intense turbulence have been made (Ref 6), but in the real atmosphere near ground level, experiments designed to measure beam deflection have found scintillations of the total beam intensity to be below detectability over paths as long as 1380 meters (Ref 7).

Interferometry to detect phase differentials across the laser profile in the atmosphere has also been used (Ref 8). This technique requires a relatively large diameter collimated beam, and since the measurements refer to a correlation distance across the beam, the scale sizes of the turbulence effects being observed are limited or truncated.

Dual beam interferometry measurements have been made from high flying aircraft to ground stations (Ref 9), and can provide a total path integrated C_n^2 when suitable assumptions are made about the power spectrum of the turbulence.

Measurements of spot dancing or beam wander have been performed in the laboratory under controlled conditions of path turbulence as well as over short to medium length atmospheric paths. Good agreement has been found relating C_n^2 derived from the standard deviation of spot deflection with C_n^2 determined from temperature probe measurements (Ref 7). The use of this technique to determine altitude variations of C_n^2 depends primarily upon the ability to measure very small scale motion of the received laser spot after propagation over a short path and at high altitude where index of refraction effects are small.

SECTION III

BALLOON-BORNE LASER BASED MEASUREMENT

After examining the methods outlined in Section II, we conclude that the potentially highest signal/noise for in situ measurement of the altitude profile of C_n^2 applies to a balloon-borne instrument which determines optical index of refraction effects by measuring spot dancing (or beam wander) of a laser beam after transit through an atmospheric path. The development of small light weight detectors which sense the position of the centroid of an incident light beam have made this approach practical. Characteristics of such a system are explored below.

GENERAL DESCRIPTION

One general instrument configuration originally investigated is the dual balloon-system as shown in Fig 1a. This design appeared at the outset to provide measurement capabilities superior to the conventional single balloon radiosonde method Fig 1b. The two balloon system is described here although it is now considered less suitable for this type of measurement.

Dual Balloon System

The main support structure is essentially an optical bench, semi-rigidly attached to two meteorological balloons. Tether lines to the balloons are attached to a trailing package which contains a telemetry transmitter and batteries which power the entire instrument. The optical path supports contain a solid-state laser, mirrors to allow multiple transit of the beam across the path ℓ, and a solid-state detector whose output may be processed to measure the position of the transmitted beam centroid on the detector.

The configuration was chosen to allow ascent measurements of the extremely small positional displacements of the laser beam to be performed forward of wake effects of the balloons (this point is further discussed

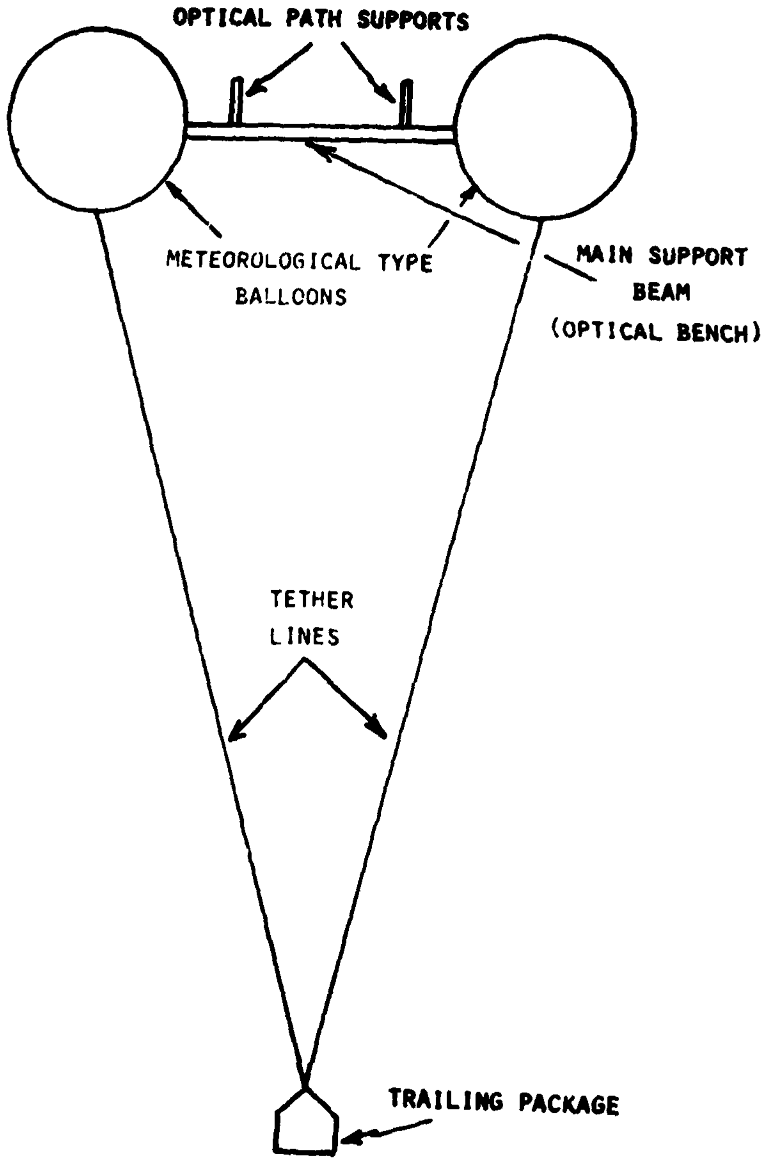

Figure 1a. Dual balloon-instrument configuration, for measurement of altitude profiles of C_n^2.

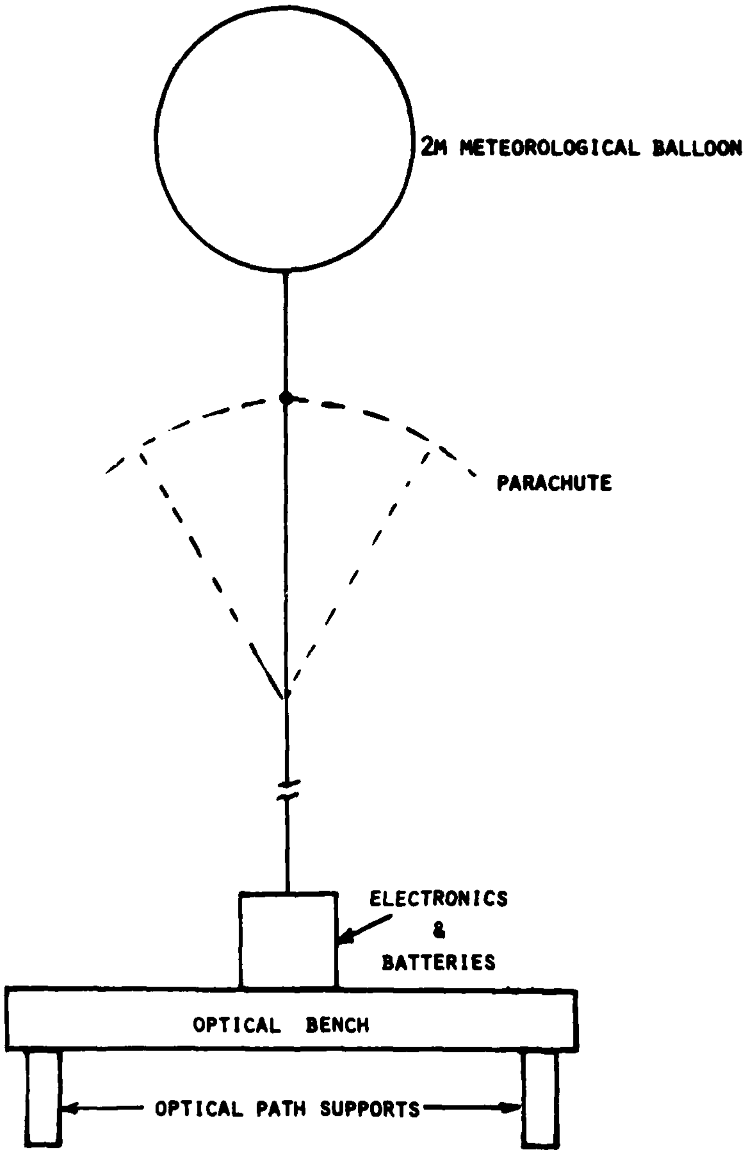

Figure 1b. Standard radiosonde configuration for measurement of altitude profiles of C_n^2.

later in this Section). An added advantage of the two balloon system as opposed to the single balloon and parachute system is the higher probability of recovering the optical bench (with its laser, detector, and position processing electronics) undamaged. Although meteorological balloons are designed to burst at approximately 25 km altitude, it is unlikely that both would burst simultaneously, and thus the instrument would then descend slowly with one balloon intact. With proper weight distribution (for example, trailing package $\sim$4.5 kg and optical bench $\sim$2.5 kg) as soon as the trailing package contacted the ground there would be excess lift on the optical bench to slow its descent. The remaining balloon and instrument would rise to the length of the tether line and be highly visible for recovery.

The two balloon system was investigated as an alternative to the conventional radiosonding technique in which the instrument package is suspended on a long tether below the balloon. It was initially thought that this configuration would position the instrumentation forward of the balloon wake effects (on ascent) to allow precise measurements on the atmosphere undisturbed by the passage of the balloon. The meteorological type of balloon orginally proposed will not function properly in this configuration, since an initial 2 meter balloon diameter at ground level becomes a 10 meter diameter at approximately 30 km altitude. This diameter would not only create wake effects extending into the measurement area, but would also present problems in the mechanical linkage of balloon to instrument. Furthermore, it is likely that the system would become unstable as balloon diameter increased.

These objections could be overcome by utilizing constant volume (or nearly so) balloons. However, the increased weight and decreased lift would necessitate an increase in scale size of the entire instrument, considerable increase in cost, provision for releasing helium from one balloon (or exploding it) to terminate the flight, and reduced ability to operate because of FAA regulations.

Single Balloon System

In light of the numerous problems of the two balloon system it is considered that the standard radiosonde method or use of the instrument on a large research balloon is preferred. A further possible application would be to use the instrument on a tethered balloon which could be reeled up and down for extended study of low altitude (to ∿1 km) variations in C_n^2. The following design assumes that the instrument is suspended on a long tether below a two meter meteorological balloon as in Fig 1b. Measurement which are least contaminated by wake effects would be accomplished on descent where the measurements are made forward of the instrument motion.

SPECIFIC INSTRUMENT DESIGN -- SINGLE BALLOON

Construction of a light to medium weight instrument to measure beam wander presents questions that cannot be definitely answered without experimental determination of whether the components of the design will perform as desired. We will assume here that the components proposed function to the limits specified by their manufacturers.

The optical bench and path supports will be constructed of high density styrofoam to limit weight and comply with FAA regulations concerning metal objects. Flexing of this material in 3 meter lengths is fairly large and thus dictates that in order to fold the beam to achieve longer path length, corner cube prisms or mirror assemblies be used to eliminate mechanically induced deflection of the laser beam in one axis. Two axis corrections would be exceedingly difficult and accordingly the instrument will be limited to measuring beam deflections in one axis only. Thermally induced difference in path length may be compensated for when the data is processed. The arrangement of laser, detector, and reflectors are indicated in Fig 2. The small beam divergence of the laser chosen (Laser Diode Labs SCW30, 5 mw at 0.8-0.89μm, single mode, 5 mR divergence) lends itself to focusing by a lens to a small spot on the position sensing detector. The f number of such an optical system is selected to collect all of the power output of the laser (effective f number 200) for focusing

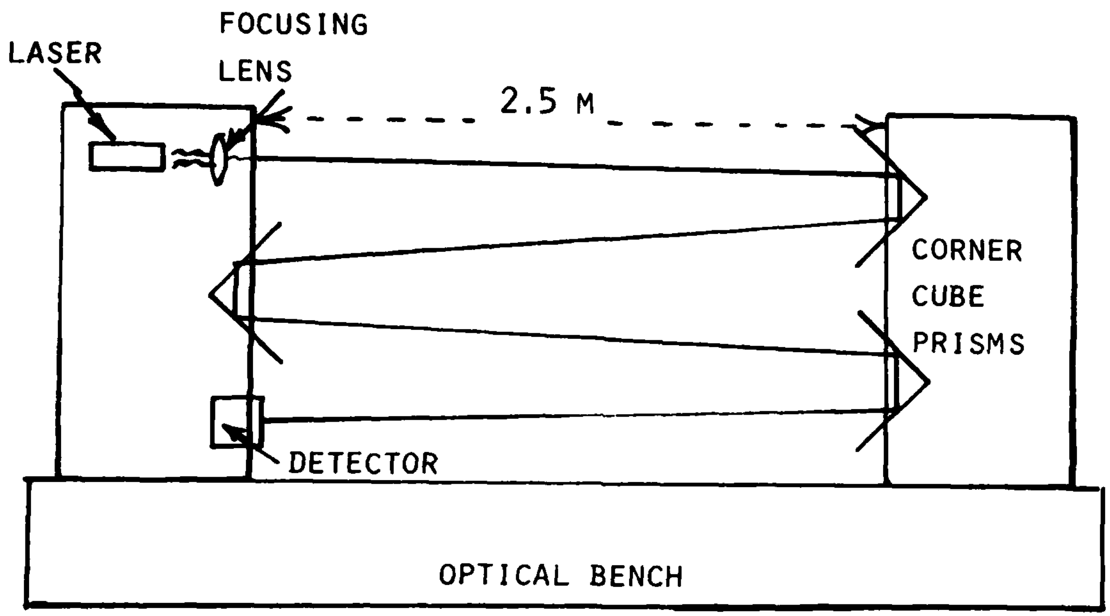

Figure 2. Schematic of instrument optical path and components.

onto the position detector. Some laser power is lost with each reflection along the folded optical path (conservatively, 90% reflection at each surface or approximately only 50% of the light leaving the focusing lens will reach the detector). It may also be necessary to insert an aperture plate between the laser and the lens to limit the size of the imaged laser beam on the detector to approximately 1 mm diameter.

Spatial characteristics of the laser speckle pattern are considered to be unlikely to affect the measurement capability of the system since they are very small scale random differences and the entire beam will be incident on the detector. The center wavelength of the laser will also change with temperature ($\sim$2-3 Å/°C) which is relatively unimportant in light of the detector characteristics (see below). Temperature dependent variation of laser power output will affect the sensitivity of the position measurement; however, temperature will be known from a radiosonde telemetry package and additionally the total current output of the detector (proportional to incident illumination) can be monitored.

The detector is a Silicon Detector Corp dual axis position sensing detector (SD-386-22-21-251), which has an active area of 9.8 mm x 9.8 mm. Maximum sensitivity is at a wavelength of 0.95μm and approximately 80% sensitivity is retained at the lower emission limit of the laser (0.8μm). The dual axis detector was chosen since flexing of the optical bench has only been corrected for in one axis; flexing in the other axis could easily move the received beam off the narrow (3.7 mm wide) single axis version of the detector.

Positional measurement capability of the detector may be calculated from

$$S = 4 \times 10^{-4} \sqrt{\Delta f / P}$$

where S is the minimum detectable change in position of the centroid of beam impinging on the detector in Å, Δf is the system bandwidth in Hertz, and P is the total light power on the device in watts. The laser and optical systems can deliver at least 0.009 mw of power to a focused spot 1 mm in diameter; allowing for a band width of 500 Hz, $S \approx 3 \times 10^{-4}$μm.

Thermal sensitivity of the detector is 1μm/°C drift in the null point. This large factor will produce only a smooth long term trend (due to the large size and therefore thermal inertial of the device) which may be removed when the data stream of individual measurements is analyzed.

Let us now investigate the range of displacement of the beam which can be expected over the altitude range from 0 to 20 km altitude and varying turbulence conditions. Using the equations derived in Ref 10, and estimating ranges of C_n^2 and L_o encountered over the altitude range, we have

$$< \rho^2 > = \frac{1.71\ C_n^2\ f^3}{W_o^{1/3}}\ B(N,\Delta)\ -\ \frac{1.56\ C_n^2\ f^3}{L_o^{1/3}}$$

where $< \rho^2 >$ is the variance of the displacement of the beam for a focused beam measured at the focal distance f, W_o is the beam diameter at the transmitter, and $B(N,\Delta)$ is a beam wander coefficient. $B(N,\Delta)$ is taken from Ref 10 as 0.9, where N is the Fresnel number of the beam $\pi W_o^2/\lambda f$, and Δ is the inner scale parameter, $\ell_o/\sqrt{\lambda}$; λ is the wavelength emitted by the laser and ℓ_o is the inner scale of the turbulence. Table 1 is a compilation of expected values of these parameters at 0 and 20 km. The ρ values in Table 1 represent the 1 sigma level of the expected beam displacement. The smallest expected deviation at this level is a factor ten larger than the minimum detectable position change, and thus it would be expected that beam displacements of this order of magnitude will be detectable. Figure 3 shows expected values of beam deflection for strong and weak turbulence at different altitudes as a function of optical path length, and demonstrates the need for a folded optical system to achieve a longer path and therefore larger deflection.

Current outputs from the position detector require processing to provide the position of the laser beam centroid. Fig 4 shows in block form the necessary components to provide an analog position output. Processing for the channels is identical, hence only the Y-axis channel is shown. All amplifiers must have low noise characteristics because of

TABLE 1

Approximate values of turbulence and instrument parameters
for weak and strong turbulence at two altitudes

Altitude (km)	C_n^2 $(m^{-2/3})$		ℓ_o(m)	L_o(m)	f (m)	W_o (m)	$<\rho>$ (μm)	
	Weak	Strong					Weak	Strong
0	6.4×10^{-17}	2.5×10^{-13}	0.001	1	10	0.04	0.43	27
20	4.55×10^{-21}	1.77×10^{-17}	.005	2	10	.04	.0038	.24

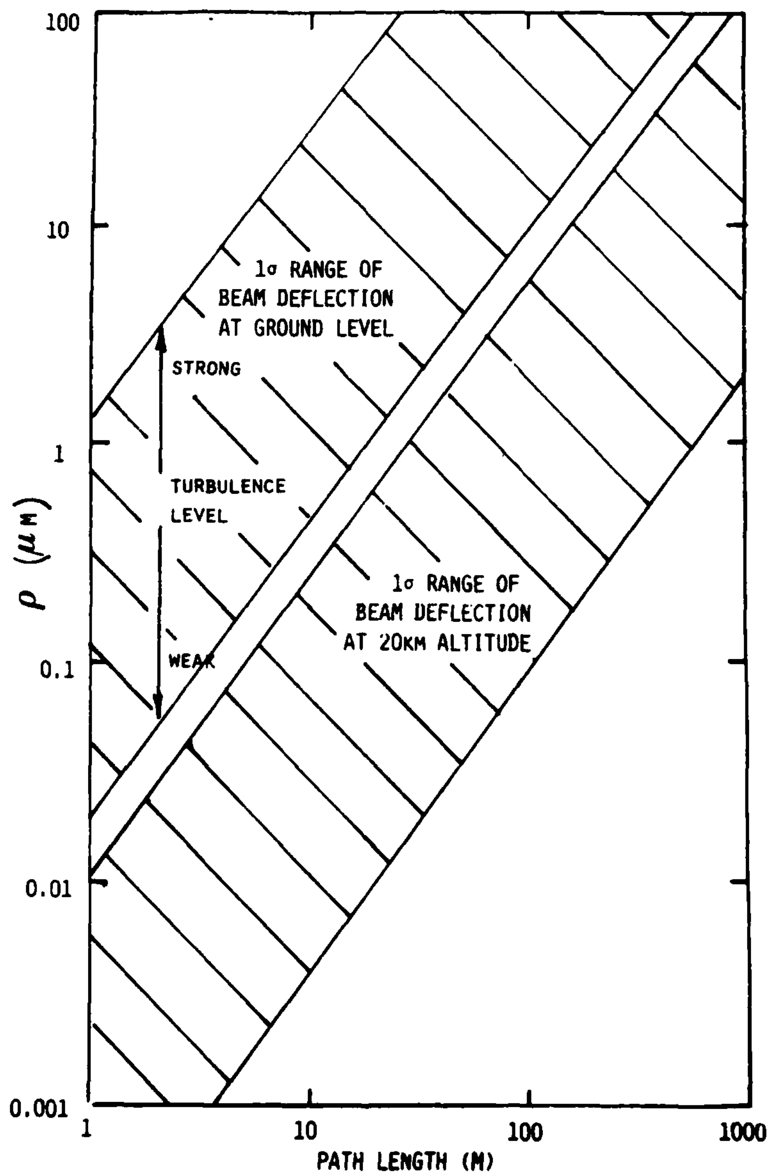

Figure 3. Ranges of expected beam deflection as a function of path length for two altitudes. The upper and lower limits of deflection correspond to strong and weak turbulence conditions respectively.

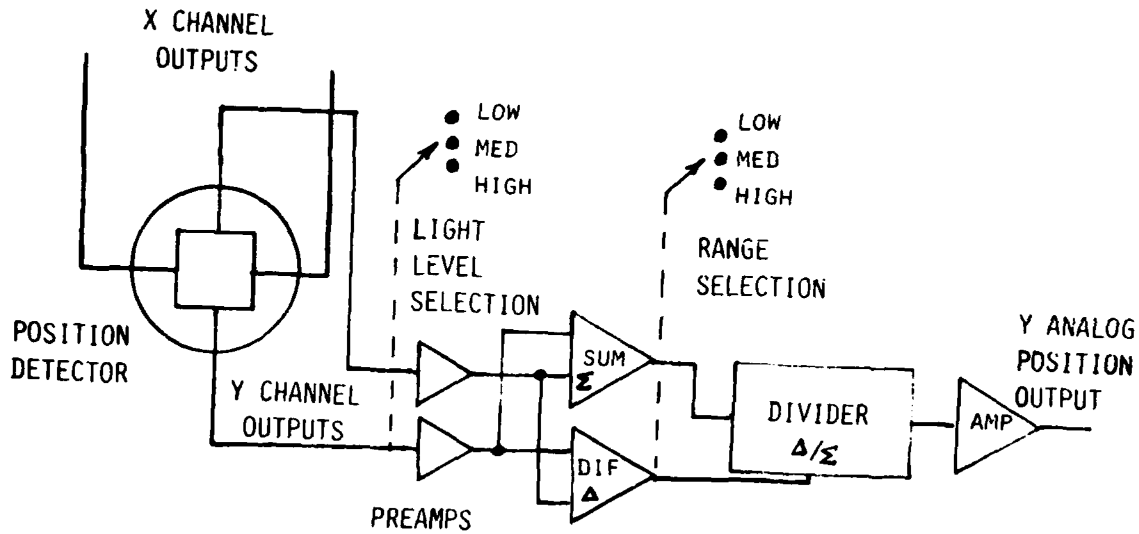

Figure 4. Block diagram of processing to obtain position information from the position sensor.

the small currents available from the detector. The analog output is presented as a fractional part of the operating range as determined by the amount of light incident on the detector and operating ranges selected for the amplifiers.

Fig 4 has been simplified as light level selection and range selection may need to be automated; it would thus be necessary to transmit at least one range selection indicator bit with the position outputs. A low illumination level would be preferred to obtain picoamp resolution (equivalent to $\sim 1 \times 10^{-4}\mu m$) of the detector outputs needed to measure small beam deflections. At larger beam deflections the range control must be changed to medium or high, resulting in lower resolution. For deflections near the full scale detector limit of ± 4.9 mm, the resolution is on the order of 0.5µm.

Operational amplifiers of sufficiently low current noise and bias drift are available from at least one manufacturer (Analog Devices). Operating temperature ranges of MIL SPEC versions of these amplifiers are -55°C to 125°C. The detector itself however is only rated to a low temperature limit of -25°C, which could limit the operating altitude of the instrument, or at least necessitate more complex temperature corrections above approximately 6 km altitude under average atmospheric conditions. Temperature response of the system must in any case be calibrated out to provide the means of correcting the data during processing.

Power requirements for this portion of the system (detector and electronics) are ± 15 volts at approximately 40 ma or about 1.2 watts, which could easily be provided by two standard radiosonde batteries (18 V, capacity at least 200 ma for 1.5 hrs). Total weight of the system is approximately 3.5 kg which is well below the carrying capacity of a standard two meter diameter meteorological balloon. Approximate weights of different components of the instrument are shown in Table 2.

TABLE 2

Approximate weight of components of the instrument in Figure 1b.

Components	Weight (kg)
Optical bench (Styrofoam)	0.9
Corner cube reflectors (3)	.22
Electronics (includes laser and detector)	.22
Meteorological radiosonde package	.68
Second transmitter and receiver	.34
Tether lines and parachute	.45
Batteries (radiosonde) (4)	.68
TOTAL WEIGHT	3.49

TELEMETRY

A standard radiosonde package should be included in the instrumentation package to measure pressure, temperature, and humidity. Modification of the transmitter can be done to permit FM transmission of this data which will be recorded on the ground and later converted back to sensor voltage levels. The uplink receiver in the sonde may be used to turn on a high frequency modulation of the carrier allowing range from the ground station to the sonde to be determined.

A second radiosonde transmitter could be modified to transmit laser beam deflection information either as an FM modulated carrier (frequency proportional to displacement of the beam) or as serial binary data which would require on board time sampling, A-D conversion, and then serial transmission of each converted displacement value. Frequencies of the second sonde transmitter and receiver may be offset to prevent interference with the first. The second uplink could be utilized to change the gain of the position sensing electronics in response to ground command.

Transmitter bandwidth is more than adequate to handle the beam position information at an estimated rate of 50 to 100 measurements per second. A single transmitter could easily send all information, including the meteorological data; however, the multiplexing network might cost more than the addition of a second transmitter. Line of sight range of the transmitter is about 200 km which under exceptional wind conditions might be occasionally exceeded during a balloon flight.

CALIBRATION

Beam deflections due to turbulence would be extremely small over the short path length necessitated for a balloon borne instrument. Measurements of such minute displacements in beam position (and derived values of C_n^2 require methods of calibrating the instrument (primarily the position detecting sensor).

Laboratory calibration of the instrument can be accomplished in a wind tunnel with controlled or "uniform and stationary" turbulence. The system could be operated over long and short path lengths and derived C_n^2 results compared to assure that the device was capable of measuring such small deflections. At the same time comparison could be made to results obtained from temperature probe measurements or from photographic measurements of beam displacements.

OPERATIONAL CONSTRAINTS

Under average atmospheric conditions the system can be expected to function over a range of temperature from -55°C to 125°C or an altitude range of 0 to 20 km. It is likely that heat generated by the electronics will keep it functional even below -55°C ambient air temperature.

A measurement system for unrestricted use, meeting density and weight requirements of FAA regulations is possible; however some type of plastic corner cube reflectors or mirror systems would be necessary to effect beam folding.

The cost of such a light weight system would necessitate recovery of the sonde for refurbishment and subsequent flights. The parts alone would cost approximately $3,000. Electronic circuit development, modification of radiosonde packages, and assembly, alignment, testing and calibration costs must be added to this figure. Even for large numbers of sondes the cost of each instrument would probably be many times the cost of the materials, and there would also be a recovery and refurbishing cost after each flight. These cost factors might limit the capability of the system to provide large volumes of statistical information about the variation of C_n^2 .

Instrument measurement time per flight is determined by balloon rise time and by battery capacity available. Slowest practical rise is about 5 meters/sec, which is approximately 1.7 hours to the 30 km balloon burst altitude. Radiosonde batteries will provide power to the instrument and transmitters for at least 1.5 hours, and probably longer.

SECTION IV

CONCLUSIONS

Derivation of C_n^2 from measurements of laser beam spot dancing performed on a balloon platform is practical over an altitude range of 0 to 20 km. A light weight instrument may be used with a meteorological balloon with a lift capacity of approximately 4 kg, or a more substantial instrument could be part of a large research balloon payload. In either case simultaneous measurements of temperature, pressure, and humidity must be made to allow correction of the spot dancing measurements for accurate calculation of C_n^2. The most probable use of such an instrument would be to provide calibration of techniques which remotely sense atmospheric index of refraction irregularities.

The standard radiosonde configuration of a single balloon with a parachute and instrument suspended on a tether below is considered to be the most practical approach. While estimates of some parameters have been made, an experimental program would be necessary to determine precise capabilities of the system, such as minimum measurable beam deflection, operating temperature range, battery drain and expected measurement time per flight. Most importantly a method of calibration of the instrument must be devised to validate the measurements on the atmosphere.

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